Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
11 (2007) 1208–1226
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Techno-economics of biogas-based water pumping in India: An attempt to internalize CO_2 emissions mitigation and other economic benefits

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Received 2 September 2005; accepted 26 September 2005

Abstract

An attempt for the techno-economic evaluation of biogas-based water pumping systems in India has been made in the present work. The potential reduction in the amount of CO_2 released in the atmosphere due to the use of the biogas-based water pumping systems has also been taken into account in the estimation of economic benefits. The economic figures of merit such as discounted payback period, net present value, benefit to cost ratio and internal rate of return have been estimated. Results of some exemplifying calculations are presented and briefly discussed.

Keywords: Techno-economic evaluation; Biogas-based water pumping system; Economic figures of merit; Sensitivity analysis

Contents

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1364-0321/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.rser.2005.09.003

1. Introduction

Biogas technology is being seriously promoted as an important option to meet the growing energy demand of rural areas in developing countries. It provides a clean and efficient fuel for several end uses such as cooking, lighting, water pumping and other motive power applications. It also ensures the recycling of nutrients in the bovine dung and other biodegradable feedstocks to the soil. One of the promising applications of biogas is for mechanical power generation through internal combustion engines to drive pumps, generators, grinding mills and other equipments in rural areas. In India diesel engines are available that can be operated in dual fuel mode (i.e. using both biogas and diesel). This can also help reduce anthropogenic emissions besides reducing dependence on diesel.

During the last two decades, the Government of India has made considerable efforts to promote the development and dissemination of biogas plants in India [1]. Several incentives have been provided to motivate the potential users towards its adoption [2]. While domestic cooking has been the primary end use of the biogas produced, its use for domestic lighting and mechanical power generation have also been reported [3–5]. The reported number of family size biogas plants installed in the country has been gradually increasing [1]. However, there appears to be a problem in making use of the dung available with households owning less than three bovines due to unavailability of sufficient feedstock to regularly operate even the lowest size biogas plant [6]. Thus, there is a need to explore the possibility of using the available dung with such households in community size biogas plants and use the biogas produced for a suitable end use such as cooking, lighting, or water pumping. The programme on community and institutional biogas plants (CBP/IBP)

was initiated by the Government of India in 1982-83. Under this programme, the biogas is generally used for generation of motive power or electricity, besides meeting the cooking energy requirements. The Ministry of Non-Conventional Energy Sources (MNES) of the Government of India provides a central subsidy of Rs 44 000 for 15–20 m^3 biogas plants and Rs 70 000 for 25–35 m^3 biogas plants [1]. Only 3902 CBP/IBP plants have been reportedly installed up to March 2003 [1] and this number is much smaller as compared to the estimated potential [7].

In order to further promote the diffusion of community biogas plant based applications it is necessary that the viability of these systems from the viewpoint of the society is established. It is therefore necessary to study all the relevant aspects and issues affecting the economic feasibility of community biogas plant based applications to the society. The use of biogas-based systems may often lead to both tangible and intangible benefits. While all the likely tangible benefits are normally taken into account in the financial evaluation exercises, the intangible benefits (such as reduction in environmental externalities, health benefits, employment generation, etc.) are invariably not considered in the analysis [5]. A modest attempt towards studying some of the aspects related to the techno-economic evaluation of biogas-based water pumping system has been made in the present work. The valuation of costs and benefits associated with the use of a biogas-based water pumping system has been made with respect to the society. The potential reduction in the amount of CO_2 released in the atmosphere due to the use of a biogas-based water pumping system has also been taken into account in the estimation of economic benefits. The additional benefits in terms of incremental fertilizer saving have also been quantified. The economic figures of merit such as net present value, benefit to cost ratio and internal rate of return have been estimated. Sensitivity analysis has also been carried out to study the effect of uncertainties associated with some of the important input variables on the economic figures of merit of the biogas based water pumping system.

2. Framework for economic analysis of biogas-based water pumping system

Fig. 1 presents a simple framework used for economic analysis of a biogas-based water pumping system. An economic appraisal of investment in a biogas-based water pumping system would require quantification and valuation of costs and benefits associated with the installation and its operation. The approaches followed for the same are briefly described in the following paragraphs.

2.1. Valuation of costs

2.1.1. Capital cost

The capital cost of a biogas-based water pumping system consists of the labour cost of civil construction, cost of input materials (such as bricks, cement, steel, sand, stone chips, etc.), and also the costs of biogas driven dual fuel engine and the pump. The economic prices of locally available materials (such as sand, stone chips and bricks) have been valued at their market prices. The economic prices of tradable components (such as cement, steel, paint, etc.) have been valued net of taxes, duties and subsidies (http://www.indiainfoline.com; http://www.nic.in/steel; http://www.sail.co.in). Similar procedure has been used to estimate the economic cost of biogas driven dual fuel engine pump.

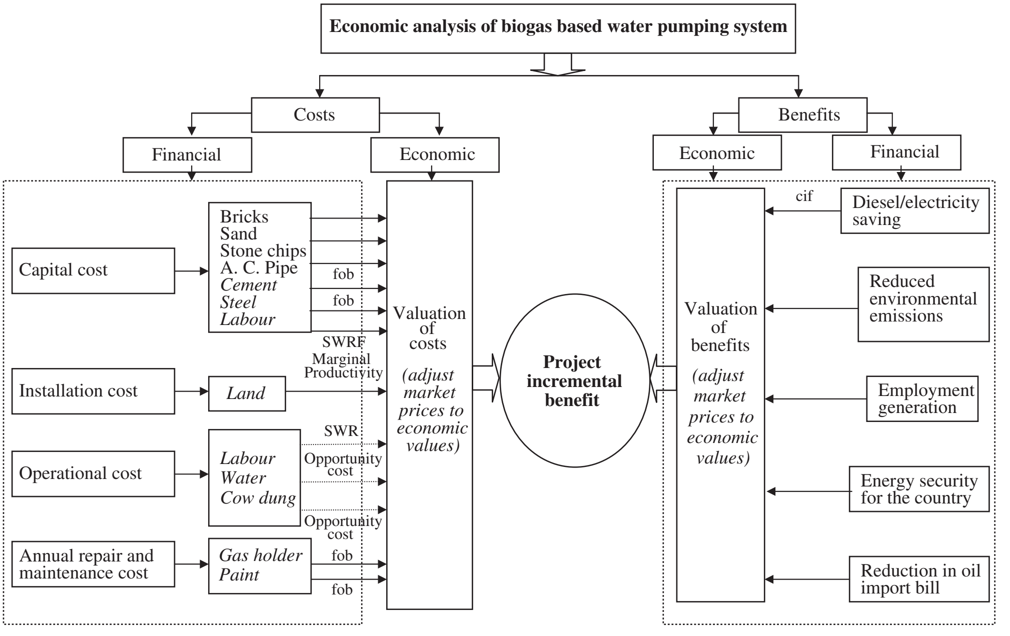

Fig. 1. A framework for the economic analysis of a biogas-based water pumping system.

2.1.2. Cost of land

The land area occupied by a biogas-based water pumping system, including that used for making input slurry and for processing digested slurry may have several alternative uses. As a first approximation, the annual economic value of the land occupied by the biogas plant and its accessories is determined on the basis of the average productivity of the land in that agro-climatic zone (Appendix A).

2.1.3. Operational costs

The operating cost of the biogas-based water pumping system includes the cost of various inputs to the biogas based water pumping system (such as bovine dung, water and diesel) as well as the cost of manpower required to operate the system. The approach used for estimating the economic value of these inputs have been described in the following sub-sections.

2.1.3.1. Valuation of labour. It is assumed that one unskilled labour is employed for a proper functioning of the biogas-based water pumping system. Different values of the opportunity costs of unskilled and skilled labour are available in the literature [3,4,8–12]. The opportunity cost of unskilled labour is often assumed to be zero in India due to considerably high unemployment levels. In the present work the opportunity cost of masons has been valued at the market wage rates and the opportunity cost of unskilled labour (in rural India) has been estimated by using a shadow wage rate factor of 0.6 [4].

2.1.3.2. Valuation of bovine dung. The economic cost of bovine dung has been estimated on the basis of monetary worth of (a) equivalent amount of fertilizer saved, (b) equivalent

amount of fuels purchased (such as fuelwood, kerosene etc.), and (c) gathered fuel (i.e. fuelwood). An average value of the economic value of bovine dung has been taken in the present work as discussed in Appendix B.

2.1.3.3. Valuation of water. The amount of water used in the biogas-based water pumping system (essentially for preparation of input slurry) is a very small fraction of the water delivered by the system ($<1\%$). Therefore, in the present work for a biogas-based water pumping system the cost of water has not been taken into account. Appendix C presents results of a study made to estimate the economic value of water used in the biogas plant.

2.1.4. Annual repair and maintenance costs

The repair and maintenance requirement of a biogas-based water pumping system usually consists of the cost of repainting the gas holder (once every year), replacement of rubber hosepipe (alternate year), replacement of gas holder (once in ten years) and the replacement, operation and maintenance cost of biogas dual fuel engine pumpset [13]. As a consequence, the costs pertaining to different components of the biogas plant are separately determined and then the total annual repair and maintenance cost is estimated.

2.2. Valuation of benefits

2.2.1. Primary benefits

The primary benefits accruing from the use of biogas-based water pumping system can be estimated in terms of the monetary value of energy source it replaces. The annual monetary worth of diesel saved, $\mathrm{MW_{ds}}$, may be expressed as

$$\mathrm{MW_{ds}} = \left[\frac{(0.746 \times 3.6)8760\,\mathrm{CUF_{bp}}P_{\mathrm{bp}}(1-\mu)\eta_{\mathrm{p,dep}}}{\mathrm{CV_d}\eta_{\mathrm{d}}}\right]p_{\mathrm{d}}(1+f_{\mathrm{p}}), \tag{1}$$

where $\mathrm{CUF_{bp}}$ represents the capacity utilization factor of the system (it is essentially the fraction of time, the system operates in a year), P_{bp} the capacity of the biogas driven dual fuel engine pump, $\eta_{\mathrm{p,dep}}$ the overall efficiency of duel fuel engine pump, $\mathrm{CV_d}$ the calorific value of diesel, p_{d} the market price of diesel, f_{p} the premium on foreign exchange, and η_{d} the overall efficiency of diesel engine pump. A derating factor, μ, has been introduced in Eq. (1) to take into account the deration in the diesel engine in dual fuel mode.

The capacity utilization factor of a biogas driven dual fuel engine pump can be estimated as

$$\mathrm{CUF_{bp}} = \left(\frac{V\eta_{\mathrm{bp}}}{24P_{\mathrm{bp}}S_{\mathrm{d,bp}}(1-\mu)}\right), \tag{2}$$

where V represents the daily biogas production capacity of the biogas plant, η_{bp} the annual average biogas production efficiency and $S_{\mathrm{d,bp}}$ the specific biogas consumption in a biogas driven dual-fuel engine.

Similarly, the annual monetary worth of electricity saved, $\mathrm{MW_{es}}$, may be expressed as

$$\mathrm{MW_{es}} = (8760 \times 0.746)\mathrm{CUF_{bp}}P_{\mathrm{bp}}(1-\mu)\left(\frac{\eta_{\mathrm{p,dep}}}{\eta_{\mathrm{e}}}\right)p_{\mathrm{e}}(1+f_{\mathrm{p}}), \tag{3}$$

where η_{e} represents the overall efficiency of electric motor pump and p_{e} the market price of electricity.

2.2.2. *Additional economic benefits*

In addition to fuel savings, the use of a biogas-based water pumping system may also provide several other associated benefits to the society. These include (a) saving of inorganic fertilizers, (b) reduction in CO_2 emissions (due to substitution of diesel), (c) employment generation, (d) reduction in uncertainty of energy supply, etc. The first two of these have been considered in the valuation of benefits in this study.

2.2.2.1. Valuation of fertilizer. Biogas plants provide fertilizer in the form of spent slurry and can therefore be compared with aerobic composting processes or with the provision of chemical fertilizers for the purpose of quantifying the associated monetary benefits. If post digestion handling of slurry is proper, it may be assumed that there is no significant change in the fertilizer value of bovine dung after undergoing anaerobic digestion [14]. Similarly, if composting is proper, farmyard manure (FYM) will have almost the same N–P–K value as the fresh dung [3]. It is assumed that prior to the installation of biogas plant (in case of a biogas driven dual fuel engine pump), a certain fraction, ς, of the bovine dung was used as a fertilizer through aerobic composting process and the remaining fraction $(1-\varsigma)$ was used as dungcakes. The additional fertilizer benefit may however arise due to the diversion of the bovine dung previously has been estimated in making dungcakes to the anaerobic digestion route estimated by using bovine dung in the biogas plant instead of making dungcakes. The monetary benefits accruing to the society from the utilization of digested slurry have been quantified in terms of the corresponding economic prices of chemical fertilizers, providing the same amount of primary macronutrients (N, P and K), as obtained from digested slurry. The annual monetary worth, MW_{fs}, due to fertilizer value of digested slurry can therefore be expressed as

$$\mathrm{MW_{fs}} = 365 V d_{\mathrm{w}}(1-\varsigma)\left\{\frac{n}{46}\,p_{\mathrm{u}} + \frac{p}{16}\,p_{\mathrm{p}} + \frac{k}{60}\,p_{\mathrm{m}}\right\}(1+f_{\mathrm{p}}), \tag{4}$$

where n, p and k respectively represent the N–P–K values (in N–P–K code) of the bovine dung, p_u, p_p and p_m the per kg market prices of urea, single super phosphate and muriate of potash respectively.

2.2.2.2. Valuation of CO_2 emissions mitigation. The method used for estimation of reduction in CO_2 emissions by using biogas for irrigation water pumping obtained from community biogas plants takes into account the CO_2 emissions from (i) the combustion of biogas (CE_{bg}), (ii) the combustion of dungcake (CE_{dc}), (iii) the inorganic fertilizer saved (CE_{fert}), (iv) the amount of net diesel saved (CE_{ds}), and (v) CO_2 embodied in the manufacturing and repair and maintenance of biogas plants (CE_{emb}). The approach used for estimation of reduction in CO_2 emissions by using biogas obtained from the community biogas-based water pumping system is presented in Appendix D.

Using Eqs. (1) and (4) the net economic benefits, $B_{i,d}$ in case of diesel substitution can be expressed as

$$B_{i,\mathrm{d}} = (1+f_{\mathrm{p}})\left[\begin{array}{c}\left\{\dfrac{(0.746\times 3.6)8760\,\mathrm{CUF_{bp}}P_{\mathrm{bp}}(1-\mu)\eta_{\mathrm{p,dep}}}{\mathrm{CV_d}\eta_{\mathrm{d}}}\right\}p_{\mathrm{d}} \\ +365 V d_{\mathrm{w}}(1-\varsigma)\left\{\dfrac{n}{46}\,p_{\mathrm{u}} + \dfrac{p}{16}\,p_{\mathrm{p}} + \dfrac{k}{60}\,p_{\mathrm{m}}\right\}\end{array}\right] + \mathrm{CE_{miti,ds}}C_{\mathrm{cem}}, \tag{5}$$

where $CE_{miti,ds}$ represents the CO_2 emissions mitigation in case of diesel substitution and C_{cem} the cost of unit amount of CO_2 emissions mitigation. The value of $CE_{miti,ds}$ has been estimated by using a framework presented in Appendix D.

Similarly, in case of electricity substitution using Eqs. (3)–(4) the net economic benefits, $B_{i,e}$, can be expressed as

$$B_{i,\mathrm{e}} = (1 + f_{\mathrm{p}}) \left[\begin{array}{l} \left\{ \dfrac{(0.746 \times 8760)\,\mathrm{CUF_{bp}} P_{\mathrm{bp}} (1 - \mu) \eta_{\mathrm{p,dep}}}{\eta_{\mathrm{e}}} \right\} p_{\mathrm{d}} \\ +365 V d_{\mathrm{w}} (1 - \varsigma) \left\{ \dfrac{n}{46} p_{\mathrm{u}} + \dfrac{p}{16} p_{\mathrm{p}} + \dfrac{k}{60} p_{\mathrm{m}} \right\} \end{array} \right] + \mathrm{CE_{miti,es}} C_{\mathrm{cem}}, \tag{6}$$

where $CE_{miti,es}$ represents the CO_2 emissions mitigation in case of electricity substitution. Once again the value of $CE_{miti,es}$ has been estimated by using a framework presented in Appendix D.

2.2.3. Employment generation

The adoption of biogas technology is expected to result in additional employment generation. The average number of mandays required for the construction of 15, 20 and 20 m^3 community biogas plants have been estimated at 104, 145 and 161 mandays (both skilled and unskilled together) reportedly. For proper operation, repair and maintenance of a community biogas plant one unskilled labour needs to be employed. Secondary employment generation benefits through a substantial requirement of diesel engines, bricks, cement, steel, stone chips etc. is also expected. However, owing to unavailability of detailed data the economic benefits due to employment generation have not been taken into account in this study.

3. Unit cost of useful energy and unit cost of water delivered by biogas-based water pumping system

The unit cost of useful energy, UUE_{bp} (in Rs/MJ), delivered by biogas driven dual fuel engine pump, can be expressed as

$$\mathrm{UUE_{bp}} = \frac{\left[\begin{array}{l} \left\{ C_{\mathrm{bp}} \left(\dfrac{d(1+d)^{t_{\mathrm{bp}}}}{(1+d)^{t_{\mathrm{bp}}} - 1} \right) + C_{\mathrm{dep}} \left(\dfrac{d(1+d)^{t_{\mathrm{dep}}}}{(1+d)^{t_{\mathrm{dep}}} - 1} \right) \right\} + C_{i,\mathrm{bp}} \\ -365 V (1 + f_{\mathrm{p}}) \left\{ d_{\mathrm{w}} (1 - \varsigma) \left(\dfrac{n}{46} p_{\mathrm{u}} + \dfrac{p}{46} p_{\mathrm{p}} + \dfrac{k}{60} p_{\mathrm{m}} \right) \right\} - \mathrm{CE}_{\mathrm{miti},i} C_{\mathrm{cem}} \end{array} \right]}{(0.746 \times 3.6) 8760\, \mathrm{CUF_{bp}} P_{\mathrm{bp}} (1 - \mu) \eta_{\mathrm{p,dep}}}, \tag{7}$$

where C_{bp} represents the capital cost of biogas plant, C_{dep} the capital cost of dual fuel engine pump, $C_{i,bp}$ the annual repair, replacement and maintenance cost of the system, t_{bp} and t_{dep} the useful lifetime of the biogas plant and the duel fuel engine pump respectively.

The corresponding unit cost of water, UCW_{bp} (in Rs/m^3), delivered by the biogas driven dual fuel engine pump, can be estimated by using the following expression

$$UCW_{bp} = \frac{\left[\begin{array}{l}\left\{C_{bp}\left(\dfrac{d(1+d)^{t_{bp}}}{(1+d)^{t_{bp}}-1}\right)+C_{dep}\left(\dfrac{d(1+d)^{t_{dep}}}{(1+d)^{t_{dep}}-1}\right)\right\}+C_{i,bp}\\ -365V(1+f_p)\left\{d_w(1-\varsigma)\left(\dfrac{n}{46}\,p_u+\dfrac{p}{46}\,p_p+\dfrac{k}{60}\,p_m\right)\right\}-CE_{miti,i}C_{cem}\end{array}\right]}{\left(\dfrac{0.746\times 3.6}{10^6}\right)\left(\dfrac{8760\,CUF_{bp}P_{bp}(1-\mu)\eta_{p,dep}}{\rho g h}\right)}. \tag{8}$$

4. Results and discussion

Table 1 presents the values of technical parameters used in the techno-economic analysis of biogas-based water pumping system [5,6,9,13,15]. The economic parameters used in the techno-economic evaluation of the biogas based water pumping system are presented in Table 2 [16–21]. The per hectare productivity of agricultural land for rice and wheat crop rotation has been estimated at Rs 261 per year (Appendix A). This being a very small amount as compared to the cost of other inputs in a biogas driven dual fuel engine

Table 1
Technical parameters used in the economic analysis of biogas-based water pumping system

Parameter	Symbol	Unit	Value
Amount of wet dung required to produce 1 m^3 biogas	d_w	kg	25
Annual average biogas production efficiency	η_{bp}	fraction	0.9
Average yield of bovine dung	D	kg	10.88
Calorific value of fuelwood	CV_{fw}	MJ/kg	16
Dungcake	CV_{dc}	MJ/kg	10
Kerosene	CV_k	MJ/litre	45
Capacity of biogas dual fuel engine	P	hp	5
Density of water	ρ	kg/m^3	1000
Derating factor	μ	fraction	0.1
Diesel replacement factor	—	fraction	0.8
Dung collection efficiency	η_c	fraction	0.75
Effective head of groundwater	h	metre	10
Efficiency of utilization of biogas dual fuel engine pumpset	$\eta_{p,dep}$	fraction	0.4
Efficiency of traditional cookstove using dungcake	η_{dc}	fraction	0.08
Fuelwood	η_{fw}	fraction	0.10
Efficiency of utilization of kerosene stove	η_k	fraction	0.40
Fraction of carbon oxidized	—	fraction	0.99
Moisture content of wet bovine dung	m	fraction	0.8
Specific diesel consumption	S_d	l/bhp-h	0.22
Biogas consumption	$S_{d,bp}$	m^3/bhp-h	0.425
Useful lifetime of biogas plants	t_{bp}	Year	25
Duel fuel engine pumpset	t_{dep}	hours	20 000

Table 2
Economic parameters used in the economic analysis of biogas-based water pumping system

Parameter	Symbol	Unit	Value
Carbon content of diesel	—	tC/TJ	20.2
CO_2 emissions in brick manufacturing	—	kg/kg	1.38
Cement manufacturing	—	kg/kg	0.49
Steel manufacturing	—	kg/kg	6.93
Through a. c. pipe	—	kg/kg	0.49
Through bitumen paint	—	kg/kg	5.3
Through enamel paint	—	kg/kg	5.3
Urea manufacturing	—	kg/kg	0.73
Super phosphate manufacturing	—	kg/kg	0.3
Discount rate	d	fraction	0.12
Fraction of carbon in dungcake	—	fraction	0.32
Fuelwood	—	fraction	0.52
Fraction of wet dung used as a fertilizer	ς	fraction	1.00
Market price of bricks	—	Rs/brick	2
Sand	—	Rs/m^3	315
Stone chips	—	Rs/m^3	400
Cement	—	Rs/50-kg bag	160
Paint	—	Rs/kg	60
Biogas dual fuel engine pumpset (5hp)	—	Rs	32 000
Urea	—	Rs/kg	6
Single super phosphate	—	Rs/kg	8
Muriate of potash	—	Rs/kg	10
Diesel	p_d	Rs/l	24
Electricity	p_e	Rs/kWh	4
Kerosene	MP_k	Rs/l	14
Fuelwood	MP_{fw}	Rs/kg	1.50
Market price of unskilled labour in rural areas	$WR_{u,r}$	Rs/man-day	75
Premium on foreign exchange	f_p	fraction	0.30
Shadow wage rate factor for unskilled labour	$SWRF_u$	fraction	0.60

Table 3
Opportunity cost of labour

Type of labour	Description	Reference (s)
Unskilled	Zero shadow wage rate	[3,8]
	50% of the wages of unskilled labour	[8–11]
	60% of the wages of unskilled labour	[4]
	66.67% of the wages of unskilled labour	[12]
Semi-skilled	68.30% of the market price	[4]
Skilled	Valued at the market price	[3]
	66.67% of market price	[12]

pump [22]. Therefore, in this study, the cost of land has not been taken into account. The market price of bovine dung has been taken as Rs 0.08 per kg [12]. An estimated value of Rs 0.20 per kg has been taken as the economic cost of bovine dung as

Table 4
Estimation of the economic cost of a biogas-based water pumping system

Components	Capacity (m^3)					
	15 m^3		20 m^3		25 m^3	
	Market price (Rs)	Economic cost (Rs)	Market price (Rs)	Economic cost (Rs)	Market price (Rs)	Economic cost (Rs)
Capital cost[a]						
Bricks	30000	30000	42200	42200	47800	47800
Sand	2835	2835	3623	3623	4347	4347
Stone chips	1280	1280	1640	1640	1720	1720
Cement	9280	7146	11520	8870	13760	10595
A.C. Pipe	7150	5506	8190	6306	8255	6356
Steel	18990	13483	22751	16153	24590	17459
Labour						
Skilled	3111	3111	4353	4353	4842	4842
Unskilled	5833	3500	8162	4897	9079	5447
Biogas dual fuel engine with pumpset (5hp)	32000	24640	32000	24640	32000	24640
Other (5% of the cost of above components)	5524	4575	6722	5634	7320	6160
Total capital cost	116003	96076	141161	118316	153713	129366
Operational cost						
Dung	5475	13687.5	7300	18250	9125	22812.5
Labour	27375	16425	27375	16425	27375	16425
Diesel	12243	15916	16325	21222	20406	26527
Total annual cost of operation	45093	46029	51000	55897	56906	65765
Annual repair and maintenance cost						
Annualized replacement cost of gas holder and biogas dual fuel engine pumpset	2129	1576	3747	2773	4916	3638
Annual cost of paint	422	393	488	454	604	562
Annualized R & M cost of biogas dual fuel engine pumpset	1500	1155	1500	1155	1500	1155
Total annual repair and maintenance cost	4051	3124	5735	4382	7020	5355

[a]US$1 = Rs 44 on April 20, 2004.

estimated in Appendix B. Table 3 presents different values of the economic costs of unskilled and skilled labour as available in the literature [3,4,8–12]. The estimates of the economic costs of different components of biogas-based water pumping system alongwith their respective market prices in the year 2002 are presented in Table 4. The annual repair and maintenance costs of the biogas-based water pumping system with different daily rated biogas production capacities have also been presented in the same table.

Table 5
Estimates of CO_2 emissions embodied in the manufacturing and repair and maintenance of biogas driven dual fuel engine pump for irrigation water pumping

Component	CO_2 embodied (kg)		
	15 m^3	20 m^3	25 m^3
CO_2 embodied in materials			
Digester	14454	19392	22158
Guide frame	1028	1028	1028
Gas holder	12625	16175	17496
CO_2 embodied in biogas driven dual fuel engine pumpset (5hp)	1395	1395	1395
CO_2 embodied in replacement and repair and maintenance			
Gas holder (once in 10 year)	25250	32350	34991
Biogas driven dual fuel engine pumpset (once in 10 year)	2790	2790	2790
Painting of gas holder (annual)	1082	1323	1547
Total	58624	74453	81405

Table 6
Annual CO_2 emissions mitigation potential of biogas driven dual fuel engine pump for irrigation water pumping

Activity	CO_2 Mitigation Potential (kg)		
	15 m^3	20 m^3	25 m^3
Reduction in CO_2 emissions due to			
Dungcakes substitution	15859	21146	26432
diesel substitution (net[a])	3995	5327	6658
Incremental fertilizer substitution	711	948	1185
Additional CO_2 emissions			
Combustion of biogas	9679	12905	16132
Manufacturing, installation and operation of biogas plant and dual fuel engine pumpset	2345	2978	3256
Net annual CO_2 emissions mitigation	8541	11537	14887

[a]The net diesel consumption has been estimated by subtracting the diesel used in the dual fuel mode from the diesel used prior to the installation of biogas driven dual fuel engine pump for equivalent amount of water output.

The economic prices of diesel, urea, single super phosphate and muriate of potash have been estimated with a premium of 30% on their corresponding market prices [3,9,23–25]. The N–P–K values have been taken as 46, 16 and 60 for urea, super phosphate and muriate of potash respectively while the values of n, p and k are 0.30, 0.30 and 0.15, respectively [5,13,14]. Table 5 presents the estimated values of lifecycle CO_2 embodied in the manufacturing and repair and maintenance of biogas-based water pumping system for irrigation water pumping. The amount of CO_2 embodied in the dual fuel engine pumpset has been estimated by multiplying its capital cost by the average value of CO_2 embodied per unit gross domestic product (0.093 kg CO_2 per Rupee) for India [26]. The net annual CO_2 emissions mitigation potential of the biogas-based water pumping systems with rated

Table 7
Valuation of annual benefits associated with biogas-based water pumping system

Benefits	Capacity of biogas plant (m^3)					
	15		20		25	
	Economic (Rs)	Financial (Rs)	Economic (Rs)	Financial (Rs)	Economic (Rs)	Financial (Rs)
Direct benefits						
Monetary worth of fuel saved						
Diesel	63666	48974	84887	65298	106109	81623
Electricity	31137	23952	41516	31936	51895	39919
Indirect benefits						
Monetary worth of fertilizers saved						
Urea	3481	2678	4642	3571	5802	4463
Single super phosphate	13345	10266	17794	13688	22242	17109
Muriate of potash	2224	1711	2966	2281	3707	2852
Total	19050	14655	25402	19540	31751	24424
Monetary worth of net CO_2 saved						
Diesel substitution	1708		2307		2977	
Electricity substitution	2513		3381		4319	
Total						
Diesel substitution	84424	63629	112596	84838	140837	106047
Electricity substitution	52700	38607	70299	51476	87965	64343

Table 8
Unit cost of useful energy and unit cost of water delivered by biogas-based water pumping system

Capacity of biogas plant (m^3)	Unit cost of useful energy (Rs/MJ)			Unit cost of water (Rs/m^3)		
	Economic analysis		Financial analysis	Economic analysis		Financial analysis
	Diesel substitution	Electricity substitution		Diesel substitution	Electricity substitution	
15	1.391	1.362	2.210	0.136	0.134	0.217
20	1.221	1.192	1.935	0.120	0.117	0.190
25	1.084	1.056	1.731	0.106	0.104	0.170

capacities of 15, 20 and 25 m^3 are presented in Table 6. The cost of CO_2 emissions mitigation is taken as Rs 0.20/kg [27]. Table 7 presents the direct and indirect benefits associated with the biogas-based water pumping system.

The unit cost of useful energy and unit cost of water delivered by the biogas-based water pumping system is presented in Table 8. It may be noted that the unit cost of water and unit cost of useful energy is low in case of economic analysis as compared to the financial analysis. Economic performance indicators have been estimated for both economic and financial considerations and presented in Tables 9 and 10 in case of diesel and electricity

Table 9
Economic figures of merit of biogas-based water pumping systems (diesel substitution)

Capacity of biogas plant (m^3)	Economic figures of merit				Financial figures of merit			
	DPP (years)	B/C	NPV (Rs)	IRR (%)	DPP (years)	B/C	NPV (Rs)	IRR (%)
15	3.34	1.41	224 096	36.70	16.93	1.03	15478	11.70
20	2.69	1.54	356 571	44.22	7.32	1.17	113931	19.69
25	2.15	1.65	503 468	53.89	4.76	1.31	228621	27.34

Table 10
Economic figures of merit of biogas-based water pumping systems (electricity substitution)

Capacity of biogas plant (m^3)	Economic figures of merit				Financial figures of merit			
	DPP (years)	B/C	NPV (Rs)	IRR (%)	DPP (years)	B/C	NPV (Rs)	IRR (%)
15	—[a]	0.88	−63861	—	—	0.62	−211 648	0.00
20	—	0.96	−27357	—	—	0.71	−188 897	6.86
25	15.33	1.03	23536	—	—	0.80	−149 928	12.31

[a]Not possible.

substitution, respectively. It may be noted that in case of the electricity substitution the use of biogas-based water pumping systems is financially not attractive. The economic performance indicators are higher in both the cases (i.e. diesel and/or electricity substitution) as compared to the financial performance indicators thus justifying the economic feasibility of community biogas based water pumping systems.

Figs. 2 and 3 show the results of a sensitivity analysis undertaken to study the effect of uncertainties associated with some of the important input variables. The unit cost of useful energy is found to be quite sensitive to the capacity utilization of the system, annual operation and maintenance cost, and useful lifetime of the system. The other two factors, i.e. discount rate and capital cost of the community biogas based water pumping system have a rather moderate effect on the unit cost of useful energy delivered by the system. A similar sensitivity curve for the unit cost of water is shown in Fig. 3.

5. Concluding remarks

The results indicate that the measures of economic performance of community biogas based water pumping systems are higher as compared to the financial measures thus justifying state support in the initial phase of their dissemination. Concerted efforts should be made for the large scale dissemination of community biogas based water pumping systems.

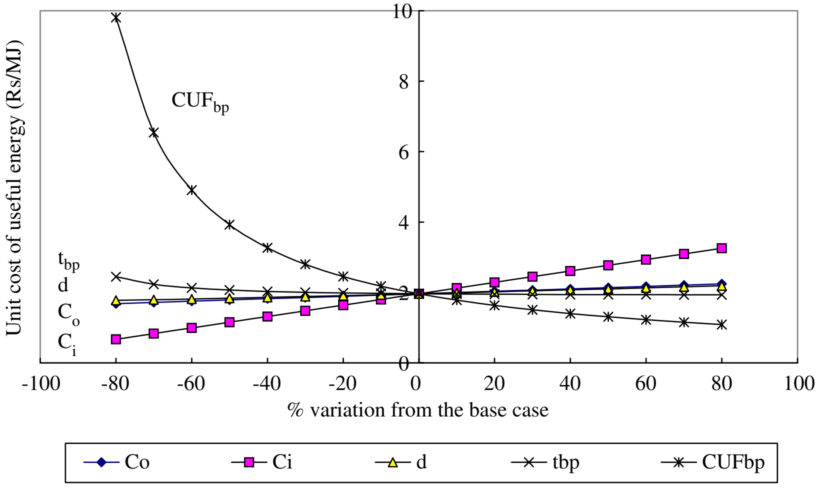

Fig. 2. Sensitivity of unit cost of useful energy delivered by a 5 hp biogas driven dual fuel engine pump (20 m^3 rated capacity of biogas plant) with respect to (i) capacity utilization factor; CUF_{bp}, (ii) useful lifetime; t_{bp}, (iii) discount rate; d, (iv) Capital cost; C_o, and (v) annual repair and maintenance cost; $C_{i,bp}$.

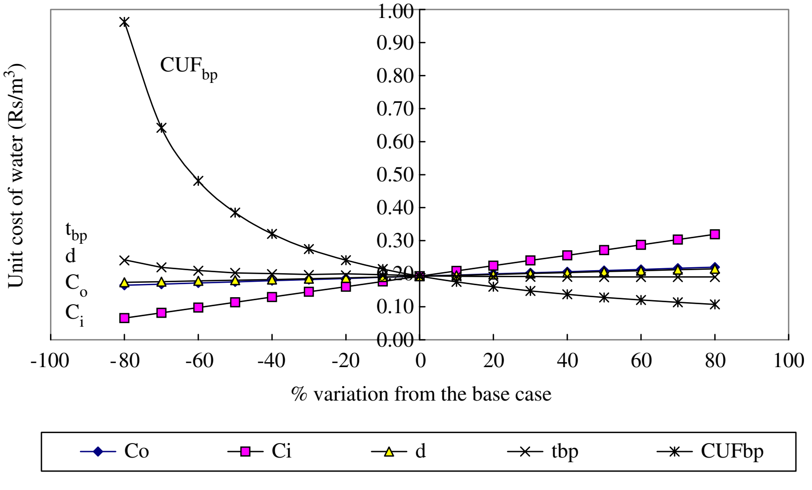

Fig. 3. Sensitivity of unit cost of water delivered by a 5 hp biogas driven dual fuel engine pump (20 m^3 rated capacity of biogas plant) with respect to (i) capacity utilization factor; CUF_{bp}, (ii) useful lifetime; t_{bp}, (iii) discount rate; d, (iv) Capital cost; C_o, and (v) annual repair and maintenance cost; $C_{i,bp}$.

Acknowledgements

The financial assistance provided by the Council of Scientific and Industrial Research (CSIR), New Delhi to the first author (Pallav Purohit) is gratefully acknowledged.

Table A.1
Economic value of land

Crop	Yield (kg/ha)	Economic value of land (Rs/hectare/season)
Rice	1985	101
Wheat	2621	160
Maize	1755	78
Sugarcane	69550	414
Groundnut	1210	148

Appendix A. Estimation of the productivity of agricultural land and its monetary worth

The productivity of the land essentially depends upon the land area under cultivation, annual crop yield and the unit price of the crop. The productivity of land with ith crop (MP_i) may be given by the following expression

$$MP_i = Y_i L_i p_i, \tag{A.1}$$

where Y_i represents the yield of ith crop, L_i the agricultural land with ith crop and p_i the procurement price[1] of ith crop announced by the government.

The land area occupied by biogas plants with three different rated capacities 15, 20 and 25 m^3 have been estimated as 41.26, 46.54 and 55.39 m^2, respectively. It is assumed that the total land area required for a 15–25 m^3 capacity biogas plant and processing of its slurry (compost pits) is around 100-m^2 [28], which may have several alternative uses. Table A.1 presents the productivity of land [22]. It may be noted that the monetary worth of land varies from Rs 78.10 to Rs 413.82 per season in case of maize and sugarcane production respectively. For the crop rotation of rice and wheat the monetary worth of land has been estimated as Rs 261 per year.

Appendix B. Estimation of the economic value of bovine dung

The economic cost of bovine dung has been estimated on the basis of (i) its worth as a fertilizer, (ii) substitution of purchased fuel(s) (such as fuelwood, kerosene, etc.), and (iii) substitution of gathered fuel (i.e. fuelwood). The procedure used for this purpose is presented in the following subsections.

B.1. Valuation of wet dung on the basis of its worth as a fertilizer

The economic value of unit amount of wet dung (EV_{wd}) may be expressed as

$$EV_{wd} = \left\{ \frac{n}{46} p_u + \frac{p}{16} p_p + \frac{k}{60} p_k \right\} (1 + f_p), \tag{B.1}$$

where n, p and k represent the N–P–K values of bovine dung, and p_u, p_p and p_k the market prices of urea, single super phosphate and muriate of potash respectively.

[1] Each year Government of India prescribes a minimum procurement price for most of the agricultural crops.

Table B.1
Economic value of bovine dung

Basis used for valuation	Economic cost of bovine dung (Rs/kg)
Worth as fertilizer	0.28
Substitution of purchased fuel	
(a) Kerosene	0.16
(b) Fuelwood	0.15
Substitution of gathered fuel	0.18

B.2. Valuation of wet dung on the basis of the substitution of purchased fuels

B.2.1. Substitution of kerosene

In the case of kerosene substitution by dungcakes the economic value of unit amount of wet dung (EV_{wd}) can be estimated by the following expression:

$$EV_{wd} = \left\{\frac{(1-m)CV_{dc}\eta_{dc}}{CV_k\eta_k}\right\}MP_k(1+f_p), \tag{B.2}$$

where CV_{dc} and CV_k respectively represent the calorific values of dungcake and kerosene, η_{dc} and η_k the efficiencies of utilization of respective end use devices, m the moisture content of the wet dung and MP_k the market price of kerosene.

B.2.2. Substitution of fuelwood

In the case of purchased fuelwood substitution by dungcake the economic cost of unit amount of wet dung (EV_{wd}) can be estimated by the following expression:

$$EV_{wd} = \left\{\frac{(1-m)CV_{dc}\eta_{dc}}{CV_{fw}\eta_{fw}}\right\}MP_{fw} \tag{B.3}$$

where CV_{fw} represents the calorific value of fuelwood, η_{fw} the efficiency of utilization of fuelwood in the traditional cookstove and MP_{fw} the market price of fuelwood.

B.2.3. Valuation of wet dung on the basis of the substitution of gathered fuelwood

In this case, it is assumed that the use of dungcake in the traditional cookstove can replace fuelwood. Thus, the economic cost of dungcakes will be the economic value of the amount of fuelwood substituted. It is assumed that the unskilled labours in the rural areas gather this fuelwood. The following expression has been used for estimating the unit economic cost of wet dung (EV_{wd})

$$EV_{wd} = \left\{\frac{(1-m)CV_{dc}\eta_{dc}UC_{fwg}}{CV_{fw}\eta_{fw}}\right\}, \tag{B.4}$$

where UC_{fwg} represents the unit cost of fuelwood gathering using unskilled labour can be expressed as

$$UC_{fwg} = \left\{\frac{WR_{u,r}}{DAFG}\right\}SWRF_u, \tag{B.5}$$

where $WR_{u,r}$ represents the wage rate of unskilled labour in the rural area and DAFG the daily amount of fuelwood gathered. To estimate the unit cost of gathered fuelwood it is

assumed that an unskilled labour in the rural area can gather 25 kg of fuelwood. Thus, the social cost of the unskilled labour will be the economic value of fuelwood gathered. Table B.1 presents the economic cost of wet dung obtained from all the above estimation procedures.

Appendix C. Estimation of the economic value of water

The economic value of water can be estimated as a sum of the cost of water pumping and the cost of its transportation to the end use point. The cost of transportation of water from its source to the end use point depends upon (i) distance between the source of water and the biogas plant, (ii) carrying capacity of an unskilled labour, (iii) number of daily trips undertaken by the manpower deputed for fetching water per day, and (iv) the wage rate of the unskilled labour. Thus, the economic value of the unit amount of water ($\mathrm{EC_w}$) may be expressed as

$$\mathrm{EC_w} = \frac{\mathrm{WR_{u,r}}}{N_\mathrm{p} M_\mathrm{w}}, \tag{C.1}$$

where N_p represents the number of daily trips undertaken by the unskilled labour and M_w the carrying capacity of the unskilled labour.

To estimate the economic value of water an example case has been taken with the assumption that water is transported from a distance of 2 km and also presents that water is available free of cost at the water source. The time taken by an unskilled labour to bring the water from the source to the biogas plant is 2 h and the carrying capacity is 25 l in a single trip. The total amount of water transported by a labour is 100 l per day. Five unskilled labours can meet the daily water requirement of a 20-$\mathrm{m^3}$ biogas plant. The market price of an unskilled labour in rural area is Rs 75/day. The economic cost of the unskilled labour has been estimated as Rs 45/manday with a shadow wage rate factor of 0.6 [4] due to high unemployment in rural India. Thus, the economic value of water has been estimated to be Rs 0.45/l.

Appendix D. CO_2 emissions mitigation potential of biogas based water pumping system

The reduction in CO_2 emissions by using biogas for irrigation water pumping takes into account the CO_2 emissions from (i) the combustion of biogas ($\mathrm{CE_{bg}}$), (ii) the combustion of dungcake ($\mathrm{CE_{dc}}$), (iii) the inorganic fertilizer saved ($\mathrm{CE_{fert}}$), (iv) the amount of net diesel saved ($\mathrm{CE_{ds}}$), and (v) CO_2 embodied in the manufacturing and repair and maintenance of biogas plants ($\mathrm{CE_{emb}}$).

(i) The CO_2 emitted from the combustion of biogas, $\mathrm{CE_{bg}}$, can be estimated as

$$\mathrm{CE_{bg}} = 365 V \eta_\mathrm{p} d_{\mathrm{CO_2}}, \tag{D.1}$$

where $d_{\mathrm{CO_2}}$ represents the density of CO_2 ($\mathrm{kg/m^3}$) at NTP.

(ii) The CO_2 emitted from the combustion of dungcakes, $\mathrm{CE_{dc}}$, prior to the installation of biogas plant can be estimated as

$$\mathrm{CE_{dc}} = 365 V d_\mathrm{w} (1-m)(1-\varsigma) C_\mathrm{dc} \left(\frac{44}{12}\right), \tag{D.2}$$

where C_{dc} represents the carbon content of dungcake and m the moisture content of wet dung.

(iii) CO_2 emissions in the manufacturing of the inorganic fertilizer replaced, CE_{fert}, can be estimated by the following expression:

$$CE_{fert} = 365V(1-\varsigma)d_w\left[\left(\frac{n}{46}\,CE_N\right) + \left(\frac{p}{16}\,CE_P\right) + \left(\frac{k}{60}\,CE_K\right)\right], \tag{D.3}$$

where d_w represents the amount of daily wet dung required to produce 1 m^3 biogas, n, p and k are the N–P–K values of the bovine dung while CE_N, CE_P and CE_K the CO_2 emissions in the manufacturing of per unit amount of urea, super phosphate and muriate of potash, respectively.

(iv) The amount of CO_2 emissions saved by diesel replacement takes into account the diesel substituted by a biogas-based water pumping system and diesel consumed in the dual fuel mode which may be expressed as

$$CE_{ds} = \left[365V\eta_p\left(\frac{S_d}{S_{d,bp}}\right)(2r_d-1)\right]\left(\frac{44}{12}\right)CV_d f_c CE_d, \tag{D.4}$$

where CV_d represents the calorific value of diesel, f_c the fraction of carbon oxidized and CE_d the carbon emission factor of diesel.

(v) Since the manufacture and installation of biogas plants involves the use of high-grade energy, certain amount of CO_2 is thus embodied in the biogas based water pumping system. The CO_2 contribution of raw materials used in the biogas plants and other direct and indirect inputs in manufacturing, installation and operation of biogas plants, CE_{emb}, is given by the following expression

$$CE_{emb} = \sum_{i=1}^{n} Y_i[CO_2]_i \tag{D.5}$$

where $i\,(1, 2, 3, \ldots, n)$ represents the material used for construction and maintenance of biogas plant (such as bricks, cement, sand, stone chips, asbestos cement pipe, paints etc.), Y_i the amount of ith material required for construction and maintenance of a biogas plant and $(CO_2)_i$ the CO_2 emissions embodied from per unit of ith material.

The net CO_2 emissions mitigation potential of using a biogas-based water pumping ($CE_{miti,\ bg}$) system has been estimated as [15]

$$CE_{miti,ds} = \left[CE_{dc} + CE_{ds} + CE_{fert} - CE_{bg} - \frac{CE_{emb}}{t}\right], \tag{D.6}$$

where t is the useful lifetime of biogas plants. CE_{ds} takes into account CO_2 emissions due to the diesel combustion in dual fuel mode.

In case of electricity substitution Eq. (D.6) can be modified as

$$CE_{miti,es} = \left[CE_{dc} + CE_{es} + CE_{fert} - CE_{bg} - CE_d - \frac{CE_{emb}}{t_{bp}}\right] \tag{D.7}$$

where CE_{es} represents the CO_2 emissions mitigation by the substitution of electricity and CE_d the CO_2 emissions by the combustion of diesel in dual fuel mode.

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